Pythia8 Hidden Valley module developments

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Pythia8 HV module

Few different regimes in signature space

Theories make (dark) jets
(QCD-like theories)

$\alpha_D N_{c_D}$ small

In this talk
Can simulate with PYTHIA8

Event shapes in between

Theories don't make (dark) jets

They make

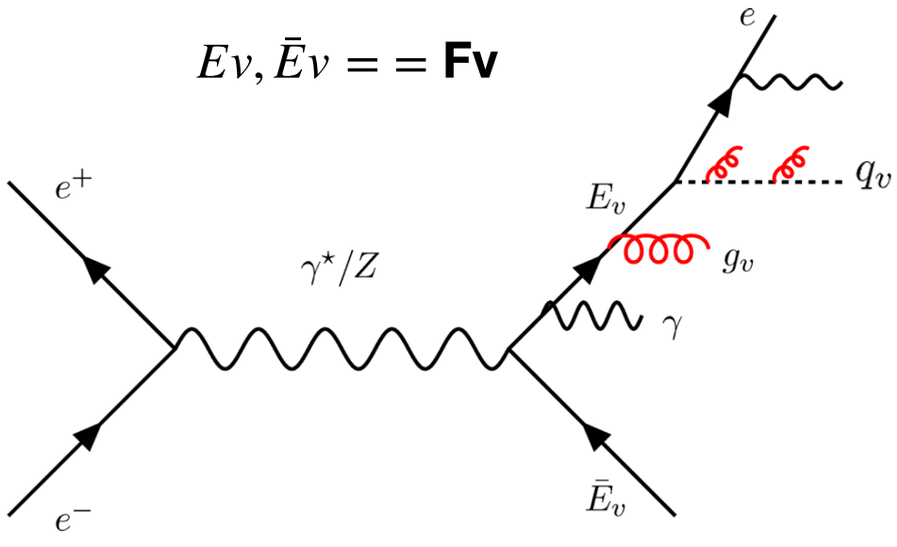
Soft Unclustered Energy Patterns (SUEPs)

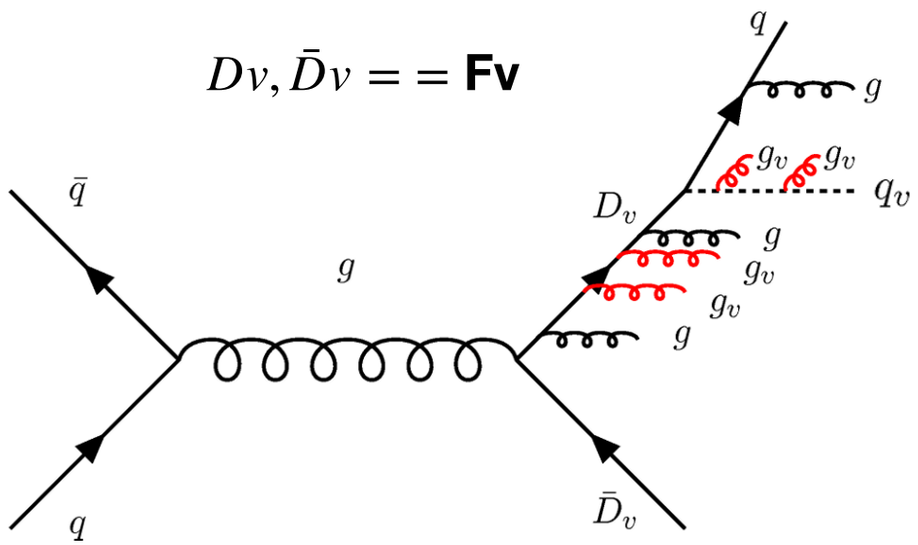
$\alpha_D N_{c_D}$ large

Not in this talk
Out of scope of current event generators

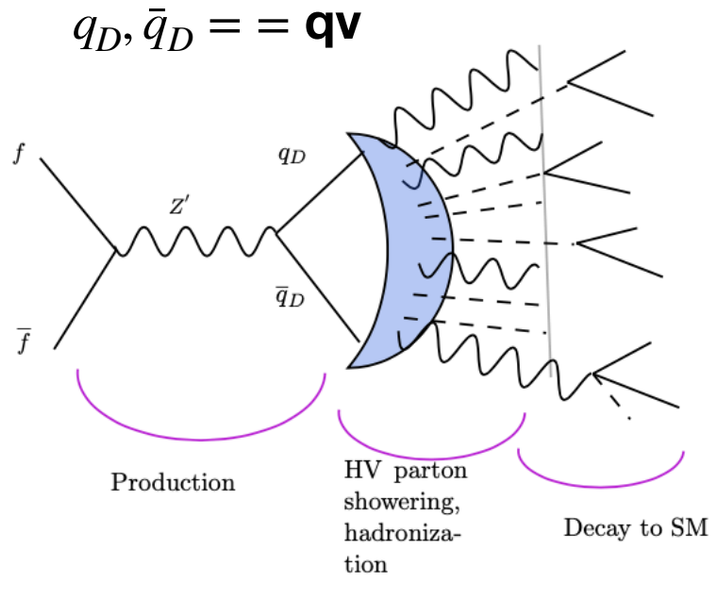
Few special tools exist

Possible HV scenarios in Pythia8





Carloni, Sjostrand arXiv:1006.2911, 1102.3795



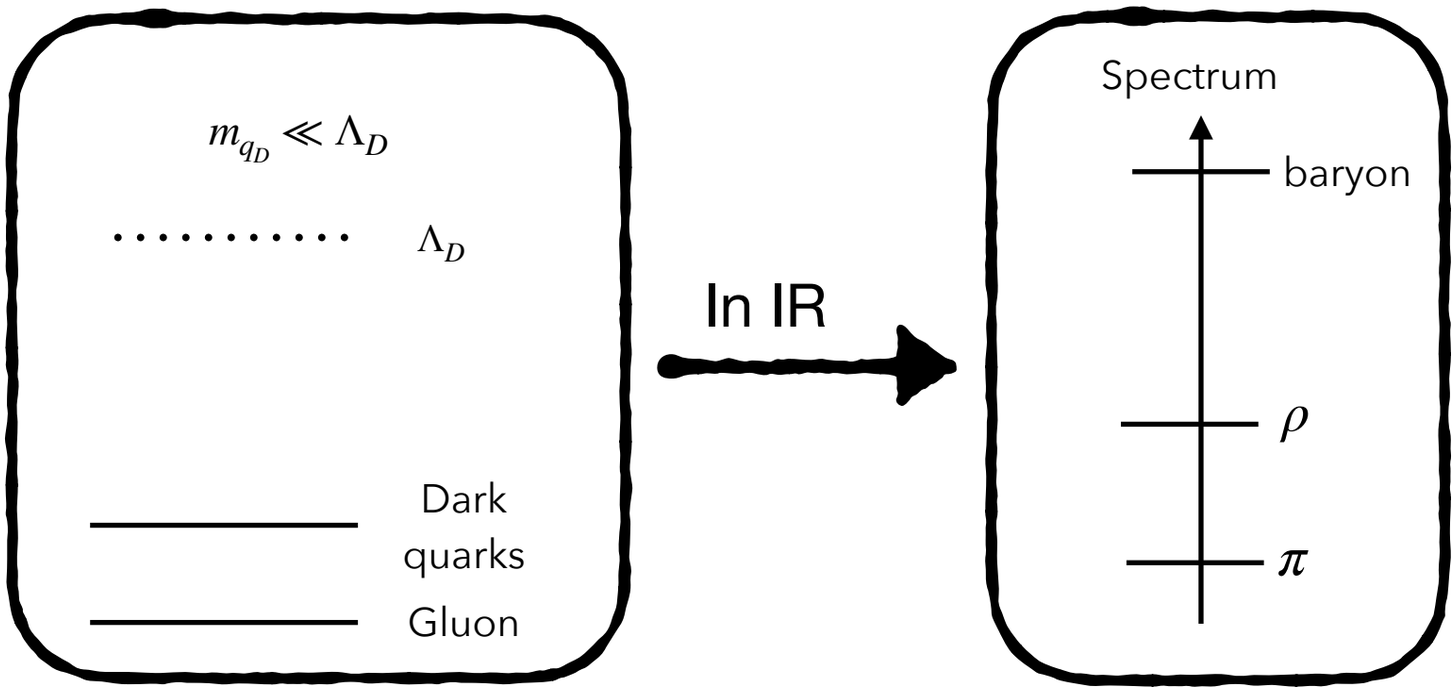
For HV landscape see M. Strassler's talk

For Herwig HV implementation see D. Stafford's talk

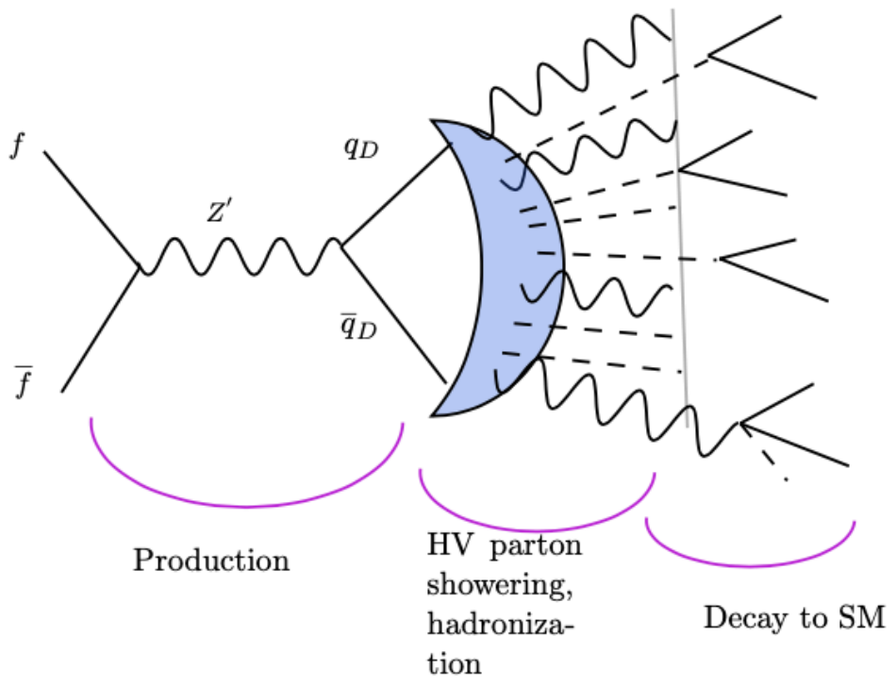
- 12 `Fv` states charged under both SM and HV group (t-channel mediator)
- `qv` state(s): charged only under HV (used for s and t-channel)
- Two HV gauges (set by `HiddenValley:Ngauge`)
  - N=1 `U(1)` (broken and unbroken): contains `gammav` (No hadronization)
  - N >1 `SU(N):` contains `gv`
- For t-channel `Fv` mediator (spin 0), for s-channel `Z'` mediator (spin-1) `qv` hadronizes in both cases

Current focus

- SU(N) N >2 scenarios: both s and t-channel
- Confinement results in bound states which leads to anomalous jets at colliders, also known as darkshowers



- My understanding is limited to s-channel scenarios, which will be the focus of the talk
- Note: scenarios we have in mind only work in QCD-like regime $N_{f_D}/N_{c_D} \to 3$



HV module pre-Snowmass status

- 4900101: **One** qv quark to represent N_{f_D} flavours of HV quarks
- $SU(N_c), N_c > 2$ theory with N_{f_D} mass degenerate quarks has $N_{f_D}^2 - 1$ mass degenerate dark rho, pions, plus 1 spin -0 and spin -1 singlet

$$\pi = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \overline{K^0} & -\sqrt{\frac{2}{3}}\eta \end{pmatrix} + \eta' \qquad \rho_\mu = \begin{pmatrix} \frac{\rho_\mu^0}{\sqrt{2}} + \frac{\omega_\mu}{\sqrt{6}} & \rho_\mu^+ & K_\mu^{*+} \\ \rho_\mu^- & -\frac{\rho_\mu^0}{\sqrt{2}} + \frac{\omega_\mu}{\sqrt{6}} & K_\mu^{*0} \\ K_\mu^{*-} & \overline{K_\mu^{*0}} & -\sqrt{\frac{2}{3}}\omega_\mu \end{pmatrix} + \phi$$

- 4900111/4900113: **One** π_D^0/ρ_D^0 state to represent all flavour diagonal species
- +4900211/+4900213: **Two** π_D^+/ρ_D^+ states to represent all flavour diagonal species
  - Anti-mesons with a -ve PID

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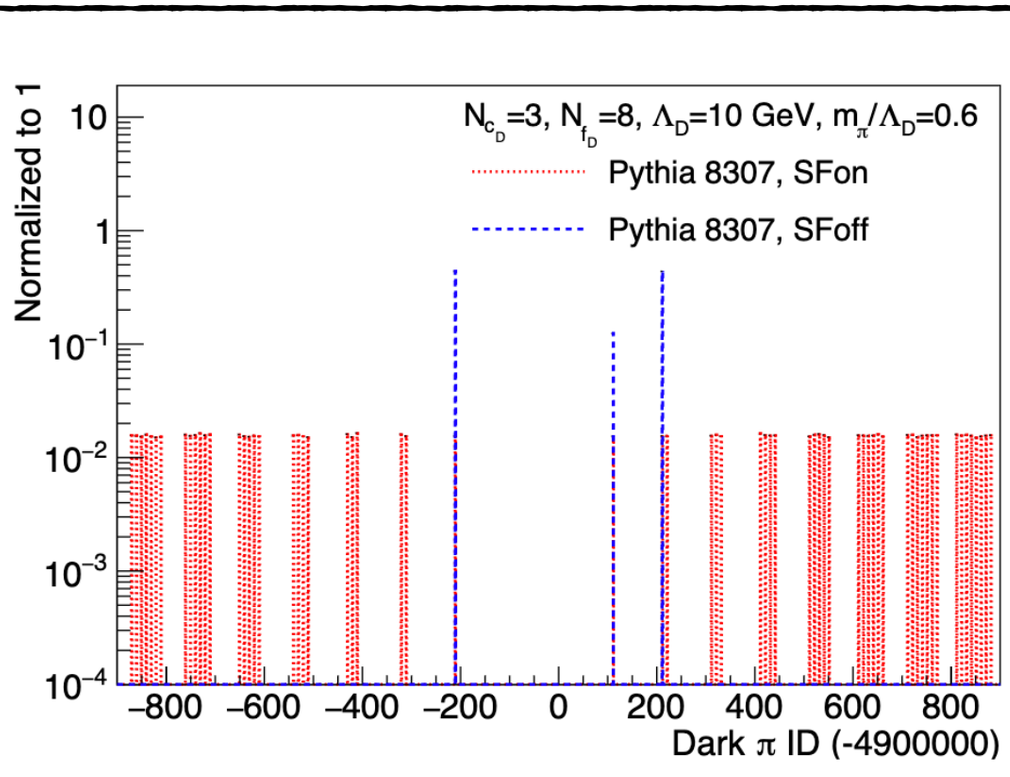
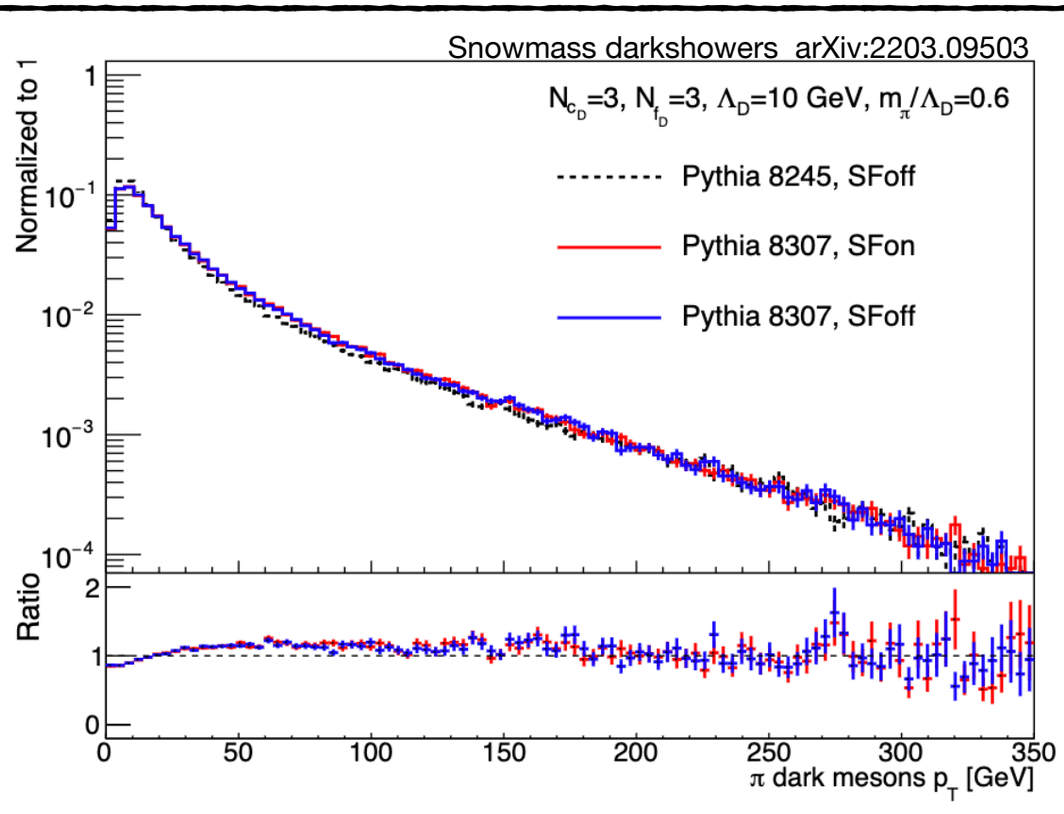
- 4900111/4900113 and (+/-)4900211/(+/-)4900213

Snowmass developments

- Extension of the HV module to 8 explicit dark quark (`qv` states) flavours
  - Correspondingly introduced 64 dark spin-0 and 64 dark spin-1 meson states
  - Possibility to set meson branching ratios and lifetimes individually
  - Set stage for mass-non degenerate theories
- Validation of HV module (s-channel properties of mass degenerate `qv` states only)
  - Reproduction of SM QCD results in the limit of HV → QCD
  - Analysis of meson production rates for mass degenerate scenarios



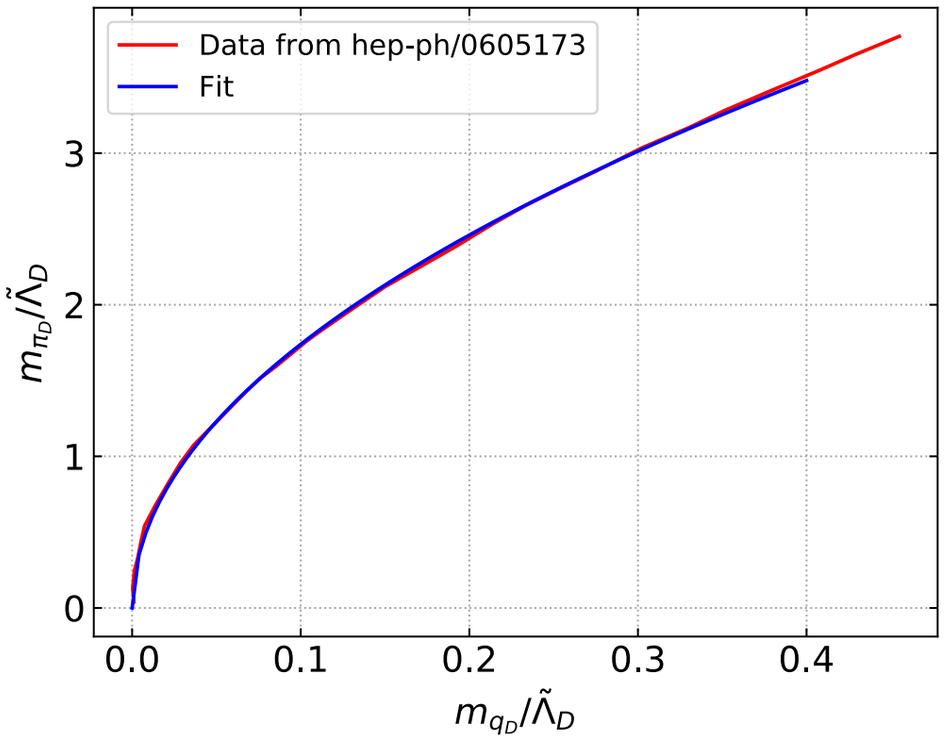


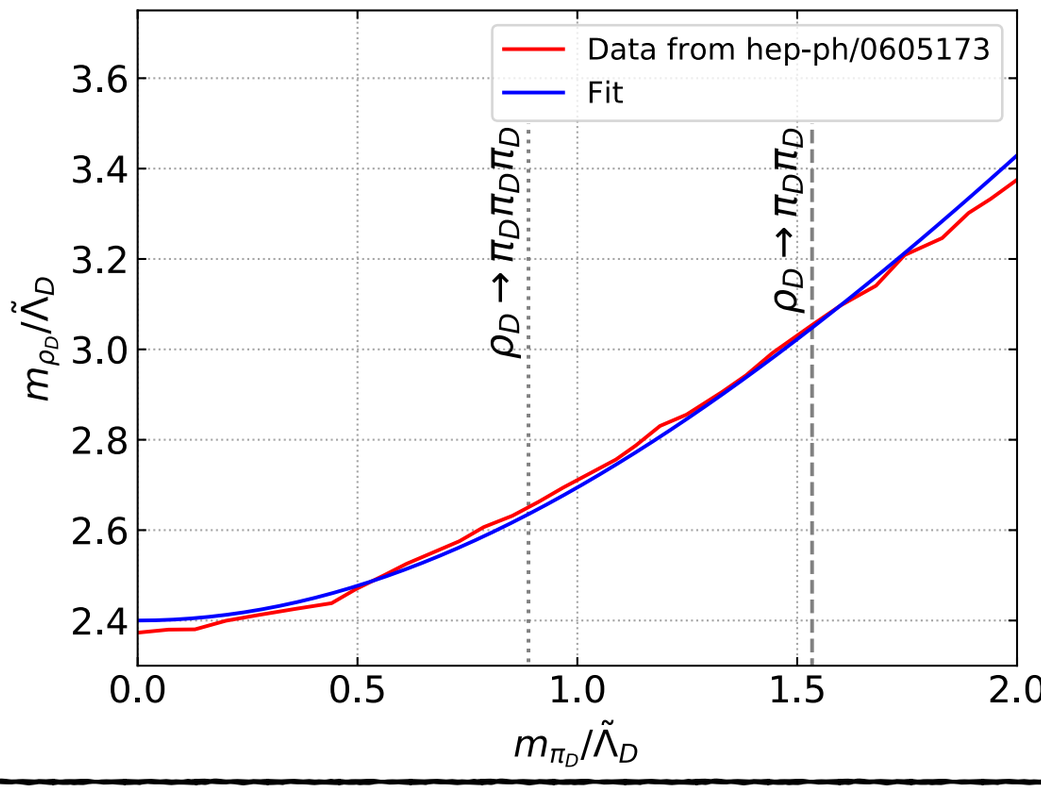
Mass spectrum

- Lattice data used to derive (N_{c_D}, N_{f_D} independent) fits

$$\frac{m_{\pi_D}}{\tilde{\Lambda}_D} = 5.5\sqrt{\frac{m_{q_D}}{\tilde{\Lambda}_D}} \qquad \frac{m_{\rho_D}}{\tilde{\Lambda}_D} = \sqrt{5.76 + 1.5\,\frac{m_{\pi_D}^2}{\tilde{\Lambda}_D^2}}$$

Snowmass darkshowers arXiv:2203.09503





- Note $\tilde{\Lambda}_D$ as a free parameter

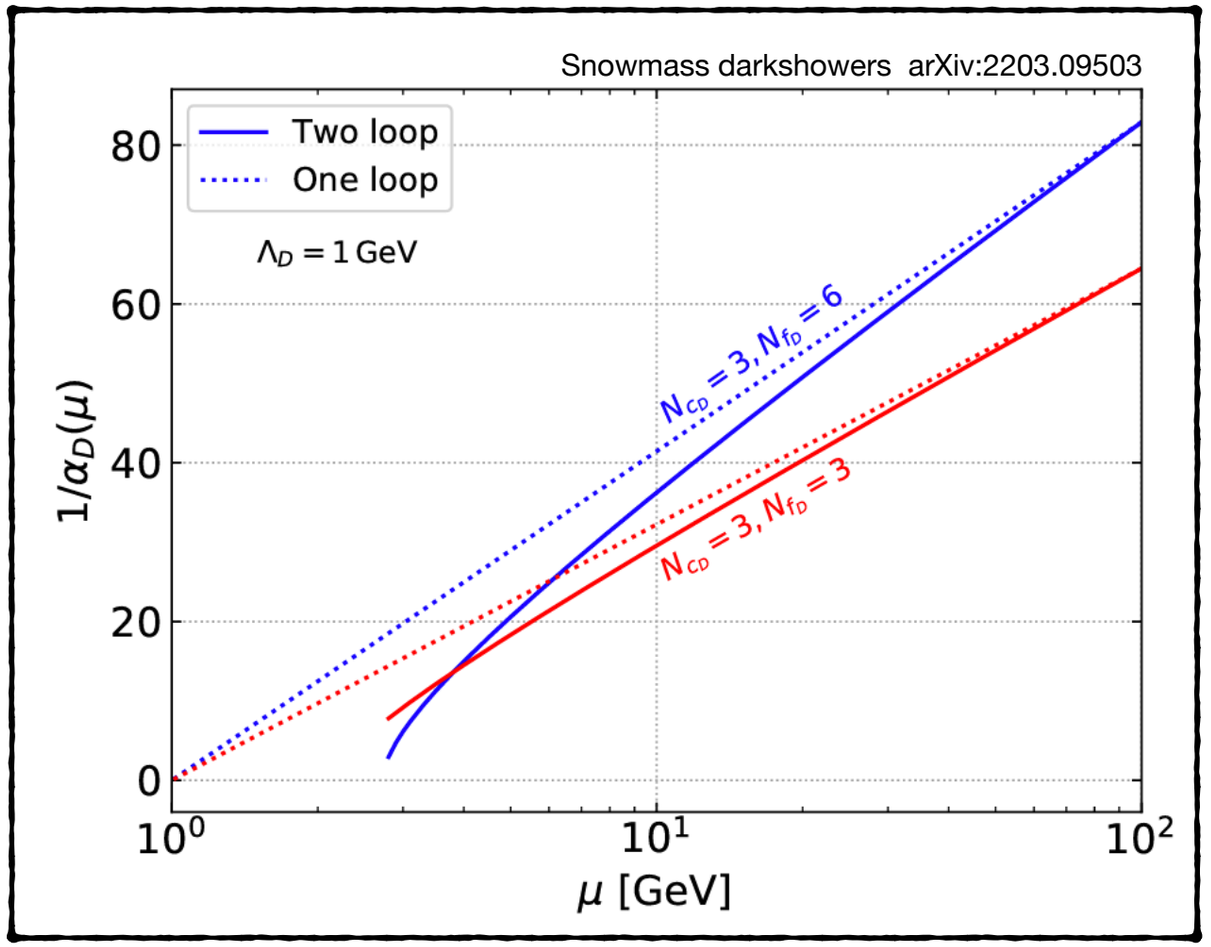
Potential improvements

- Running coupling α_D modelled at one loop, going from one to two loops makes a large difference

Running coupling at 1-loop, Λ_D defines point of divergence

$$\alpha_D(\mu^2)\, N_{c_D} = \left[\frac{1}{2\pi}\left(\frac{11}{3} - \frac{2}{3}\frac{N_{f_D}}{N_{c_D}}\right)\log\left(\frac{\mu}{\Lambda_D}\right)\right]$$

Two and three loop iterative formulae from PDG



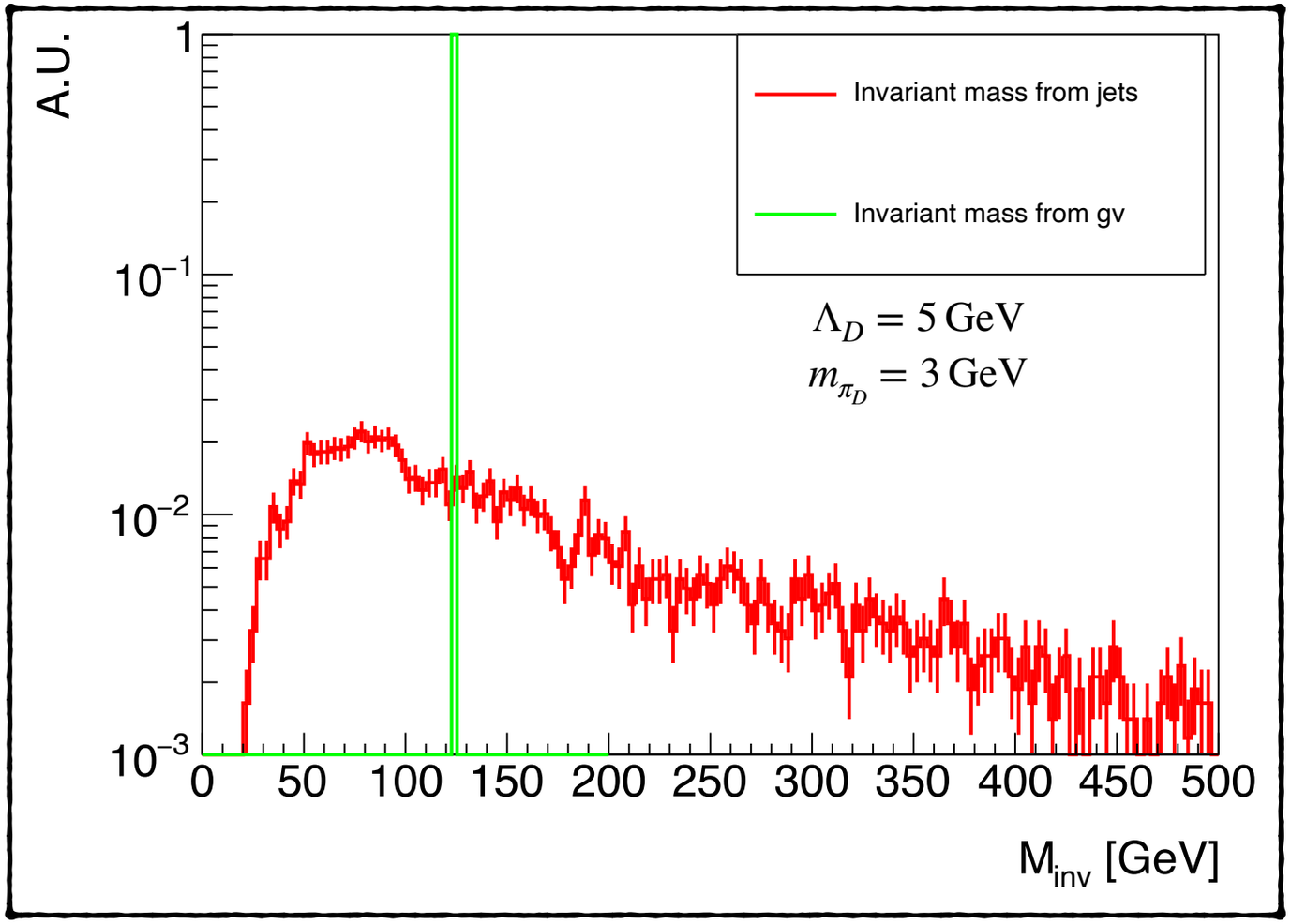
- No concrete guidelines for hadronization parameters, much needs to be explored and thought about
- Currently assumed that the scale $\tilde{\Lambda}_D$ entering in the mass fits is the same as scale at which α_D diverges. (I have had further conceptual understanding of this issue but not concrete implementation)
- Pythia8 HV is not yet validated for mass split theories

Post-snowmass developments

- A number of improvements in HV module
- `Pythia 8.308` (16 Nov 2022):
  - Explicit bookkeeping of HV colors
  - Allows for SM Higgs (`h`) to `gv gv` mode, which was previously impossible
  - Update to decay method of `ParticleDecays` class
    - Leptons emerging from decays of `gammav` can now also radiate SM photons in addition to HV radiation
  - Bug fix to unblock the radiation of HV photons in a broken **U(1)** scenario
    - Most important for `Fv` states
  - `main171.cc` now shows a sample program for HV production mechanisms
- `Pythia 8.309` (16 Feb 2022)::
  - Running coupling now implemented up to three loops

Higgs to gv gv decays

- SM Higgs to gv decays now possible

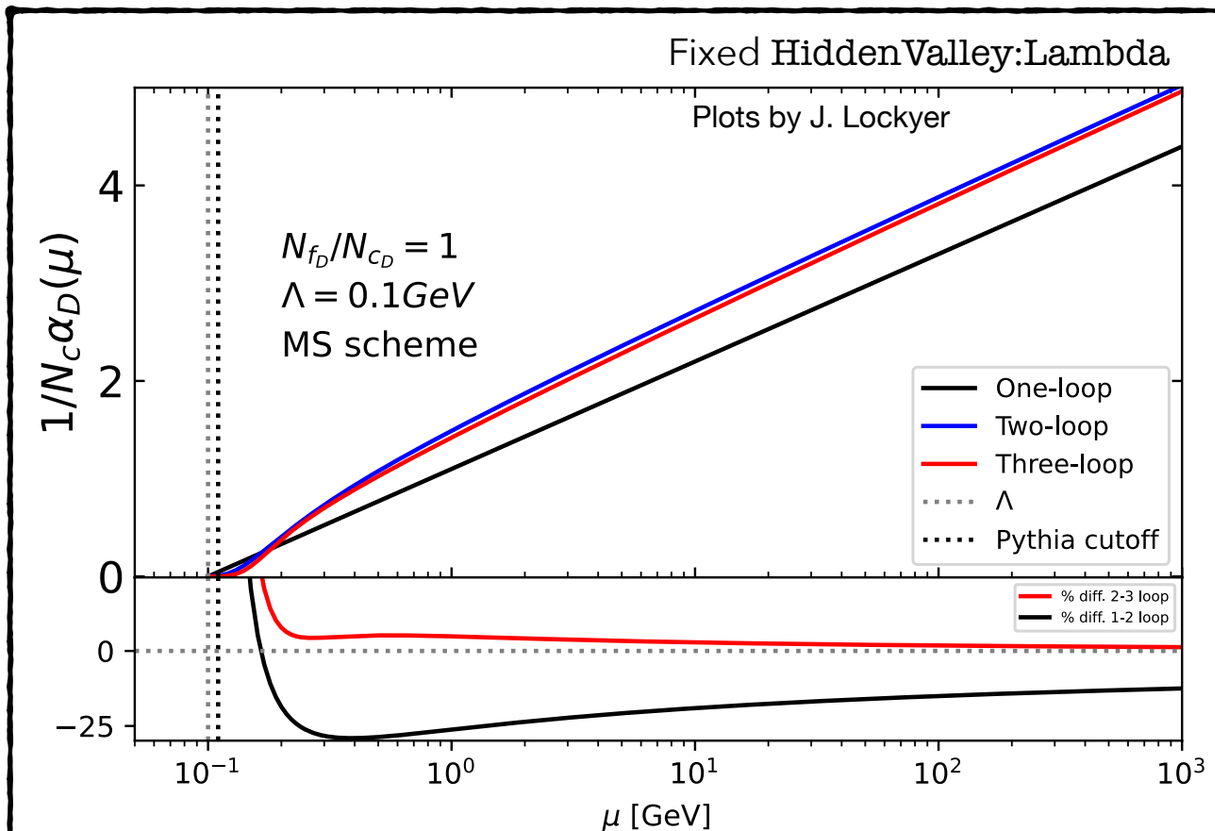


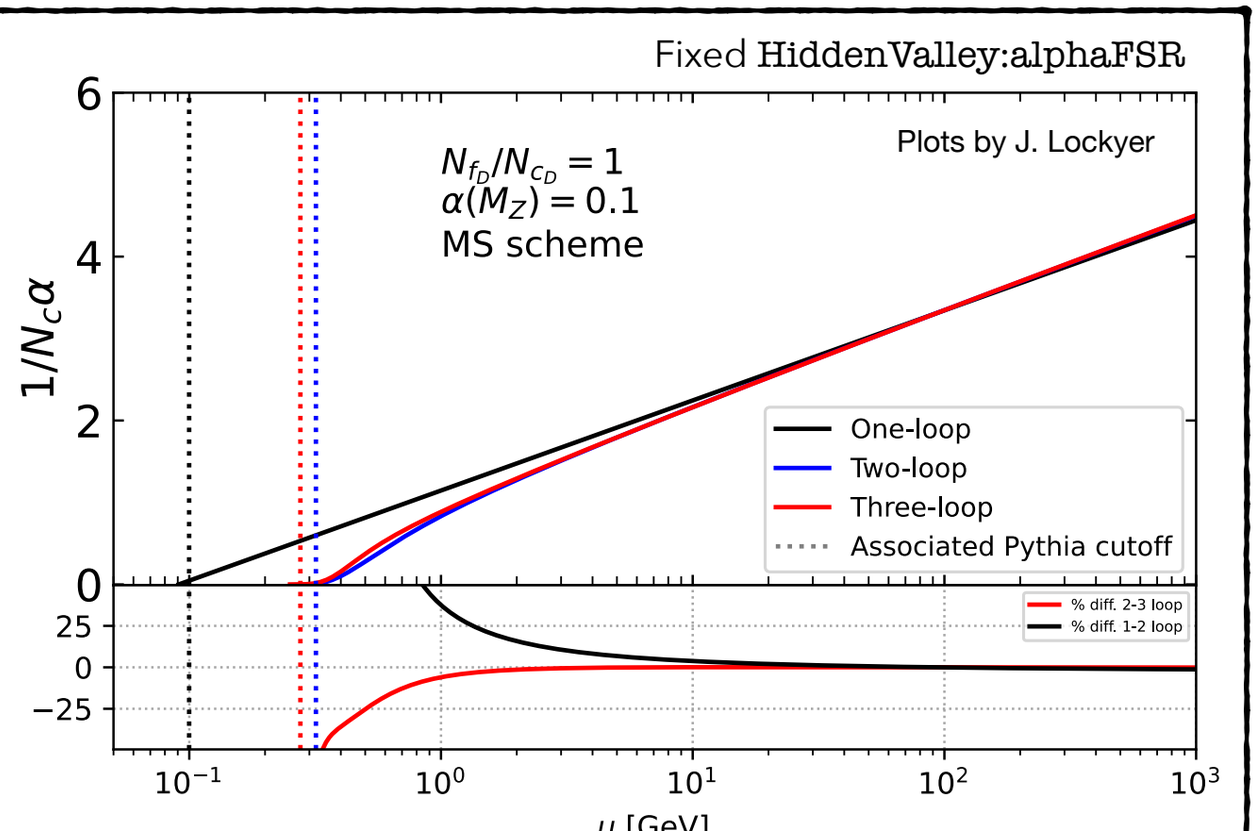
- First tests done via setting

```
HiggsSM:all = on
25:onMode = 0
25:addChannel = 1 0.1 100 4900021 4900021
```

Running coupling

- Since Pythia 8.309, it is possible to run α_D up to three loops
- Can fix HiddenValley:alphaFSR, equivalent to fixing $\alpha_s(m_z)$: in this case Λ_D between 1,2,3 loops will change
- Can fix HiddenValley:Lambda: in this case $\alpha(\mu)$ between 1,2,3 loops will change

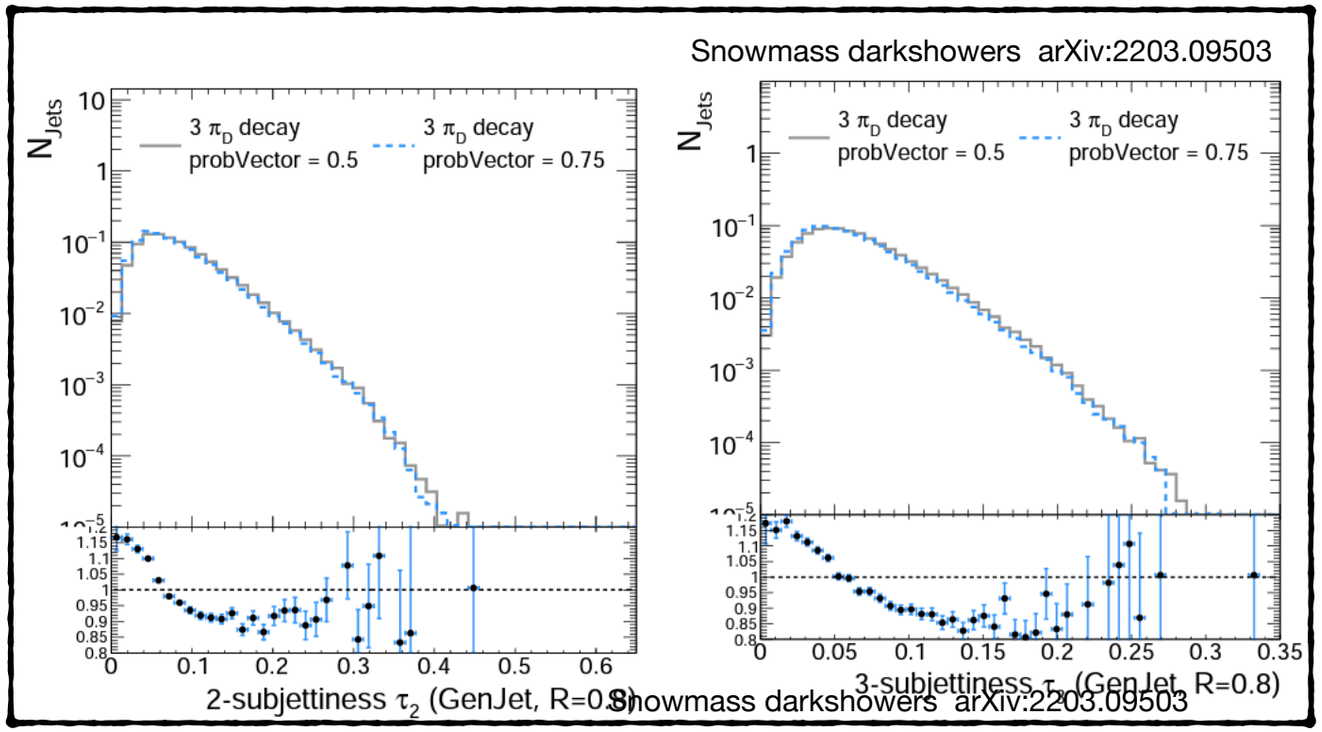




- Given that parton showers are at leading order, using higher order of running coupling may not lead to higher accuracy in event shapes

Future possibilities

- Progress towards hadronization uncertainties
  - Some progress during snowmass
  - Remains an important obstacle towards robust predictions
- Validation for mass split theories
  - What if the dark quarks have different masses? How should the generator level dark hadron production look like? What are the validation strategies?



- SU(N) matter content other than Dirac fermions?
  - What if SU(N) sector contains scalars instead of Dirac fermions?
  - It is known that the resulting spectra would look very different, how does the associated PS + hadronization look?
- Development for large Nf/Nc scenarios (see J. Lockyer's talk tomorrow ECS session)
- Non-SU(N) scenarios?
  - Sp or SO gauge groups have different colour flows and hence different details of the signatures, needs critical thinking about where/when/how to extend current frameworks.

Conclusions

- Reliable simulation tools are an important asset to make progress in HV landscape
- Took an overview of the PYTHIA8 Hidden Valley tool
- Many important improvements to ensure correctness and flexibility of the module during and after snowmass
- New and interesting darkshowers production channels added (e.g. h → gv gv)
- Ideas for future developments are chalked out but not yet implemented
- IMPORTANT: As users of the module, it is our responsibility to ensure that the tools are used in correct regimes. There are very few, if any, safety switches implemented for a good reason.
- IMPORTANT 2: I did not talk about the necessary settings to actually ensure that darkjets are generated from theoretically consistent model